N71-12748

NASA TECHNICAL TRANSLATION NASA TT F-13, 288

DETERMINATION OF SHORT-TERM VARIATIONS IN ATMOSPHERIC DENSITY FROM QUASI-SYNCHRONOUS VISUAL OBSERVATIONS OF ARTIFICIAL EARTH SATELLITES

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Translation of "Opredeleniye kratkovremennykh izmeneniy plotnosti atmosfery iz kvazicinxronnyx vizual'nykh nablyudeniy iskusstvennykh sputnikov zemli".

In: Byulleten' Stantsii Opticheskogo Nablyudeniya Isskustvennykh Sputnikov Zemli, No. 53, Issue 1, Moscow, pp. 9-22, 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 DECEMBER 1970

DETERMINATION OF SHORT-TERM VARIATIONS IN ATMOSPHERIC DENSITY FROM QUASI-SYNCHRONOUS VISUAL OBSERVATIONS OF ARTIFICAL EARTH SATELLITES

M. Ill

ABSTRACT: Results of determination of shortperiodical atmospheric density variations from quasimultaneous visual observations of satellites are presented. The conclusion is drawn that the period of the satellite can be determined with a precision of $\pm$ 0^m.0001 and its variations with that of $\pm$ 0^m.001 during one passage. Density variations with the amplitude of the order of 64.3% in two days interval were discovered for the satellite COSMOS-53.

When using the classical methods of processing ordinary visual observations /10* of artificial satellites it is not possible to study the short-term variations in atmospheric density, the duration of which forms an interval of one of two days or less. In order to study them it is necessary to use new observation and processing methods. One such possibility is the use of quasi-synchronous satellite observations. Such observations were first made within the framework of the INTEROBS program in 1962. The quasi-synchronous observations obtained within the framework of the INTEROBS program are published regularly by the publishers of the Hungarian Academy of Sciences. So far, four volumes of the results of observations by this program have been put out. These observations were used with the aim of selecting optimal methods of processing quasi-synchronous observations. One of the most important features of quasi-synchronous observations is that a maximum possible number of observations is obtained in a given time interval, that is, there are always "chains" of observations. These "chains" determine two basic advantages in processing observations.

1. From the quasi-synchronous observations it is possible to determine the synchronous topocentric coordinates of a satellite from several stations and therefore to determine the location of a satellite in space from each such synchronous pair of coordinates. Owing to this fact, in processing observations it is possible to use instead of the topocentric directions (α , δ) the topocentric or geocentric distances to the satellite or its geocentric coordinates relating to the synchronous instant. This permits the development of new processing methods.

2. Since the observations in the "chains" follow each other directly, it is possible to determine several important parameters, e.g., the instant some celestial circle is intersected, from each individual observation, independently of the others, and then to take it as the average of the individually obtained values; since in doing so the parameter is determined 20 to 60 times, the accuracy of its determination is increased. Another processing feature follows

*Numbers in the margin indicate pagination in the foreign text.

from the fact that the quasi-synchronous observations are used to study the atmospheric density, and to do so it is not necessary to determine all the orbital elements. Also determined in addition to the satellite period of revolution, which should be obtained with maximum possible accuracy, is the eccentricity e and the argument of the perigee ω, and it is not absolutely necessary to determine the rest of the orbital elements. Consequently, it is possible to determine the satellite revolution period independently of the other orbital elements. At the same time it was found to be a great advantage that this problem can be reduced to determination of the instant of passage through a chosen celestial circle. The draconic period of a satellite is obtained during this process by determining the two instants of passage through the celestial circle.

Many authors have proposed various possible methods for processing quasi-synchronous observations. For this reason the individual processing steps can be accomplished in various ways. In obtaining the variations in atmospheric density we chose the following approach.

1. From the quasi-synchronous topocentric observations we determined the synchronous coordinates in part by graphic interpolation [2], in part by numerical interpolation [3].

2. By means of computers we calculated the rectangular geocentric space coordinates of the satellite, partially by the method outlined in [4], partially by the method in [5], and also the pertinent radius - vectors x_c, y_c, Z_c, R_c.

3. The instants of intersection of the selected celestial circle were calculated by the method of I. D. Zhongolovich [1].

4. The mean period of revolution for an interval defined by the two instants of intersection is established by the following formula:

$$P = \frac{T_{\varphi\kappa} - T_{\varphi i}}{n_{\kappa, i}}$$

where $n_{k,i}$ is the number of satellite revolutions in the time interval $T_{\varphi\kappa} - T_{\varphi i}$. /11
The center of the interval is considered as the epoch at which the period is determined.

5. The draconic periods are represented graphically according to the proposal of T. V. Kasimenko and N. P. Slovokhotovoi [6] as a function of n (the numberof revolutions) and a smoothed curve is drawn from them. From this curve we extract the values of the period that correspond to each tenth revolution, and in this way we determine the variations of the period ($\Delta = \frac{dP}{dn}$). In doing so, the middle of the interval is again considered to be the epoch.

In some cases the period variations Δ were calculated on the basis of [7] (primarily to check the graphic results).

6. The values of e and ω were calculated in part by the method given in [2]; in part they were interpolated on the basis of the ephemerides. The values for H (altitude of the homogeneous atmosphere) were taken from [8].

7. The values of the atmospheric density were determined by King-Hele's formulas. Since the technical parameters of the satellite are not always known, and also because we are determining not the absolute values of the atmospheric density, but its relative variations; for $\delta = F C_D S$ we took the value $\delta = 0.1$ cm^2/g, which can be considered as the average value for an ordinary satellite. Observations extracted from the published data of INTEROBS were used. They are given in Table A.

TABLE A

Object	Time of observation
1960-05-03	Aug. 19-29, 1963
1960-05-03	July 7-12, 1964
1960-05-03	Sept. 17-27, 1964
1960-05-03	Aug. 20-26, 1965
1963-43-01	March 11-17, 1964
1963-43-01	April 9-15, 1964
1964-53-01	Aug. 10-27, 1965
1965-06-01	Aug. 22-29, 1965
1965-06-01	Sept. 16-26, 1965

With the kindly permission of the authors of [6], the instants of intersection of the latitude circle by the following satellites were used for subsequent processing:

1960-05-03: Aug. 19, 1963 Sept. 17, 1965 Aug. 20-26, 1965
1964-53-01: Aug. 19-27, 1965
1965-06-01: Aug. 22-29, 1965 Sept. 16-26, 1965

The author wishes to express his sincere gratitude to T. N. Kasimenko and N. P. Kasimenko. In processing these data, therefore, we used only steps 4-7, since steps 1-3 had already been completed by the authors of the cited reference. The periods obtained for these intervals and their variations are given in Table 1. From the table it can be seen that the period of a satellite can be determined in general with an accuracy of $\pm 0.001^m$; the accuracy of determining the period variations in one revolution is $\pm 0.0001^m$.

Under favorable conditions the accuracy may be one order greater.

A total of nine time intervals was studied. No variations in the satellite period were found in three intervals, and therefore no changes in atmospheric density; in the remaining six intervals, short-term fluctuations of the atmospheric density were found. Since the mean square errors for two time intervals proved to be of the same order as the found period variations, we did not determine the variations in atmospheric density from these values. Thus, we obtained the variations in atmospheric density only for four time intervals, where the variations of the period were considerably greater than the amplitudes of their mean square errors. The atmospheric density values we obtained are given in Table 2. The period variations from which the density values were determined are shown in Figs. 1-4. The upper curves in the figures show the time-variation of the period (as a function of the number of revolutions, calculated from the instant t_0). The lower curves show the variations in satellite acceleration (Δ). Here too we plotted the amplitudes of the mean square errors. An analysis of these results yields the following: /12

In Fig. 1 (satellite 1960-05-3, Sept. 17-27, 1964) can be seen the variation in period, which lasted for about 30 revolutions, i.e., about two days. Such a variation in period could have been hardly detected by the classical methods, on the basis of ordinary observations. In Fig. 1 it is evident that Δ (variation in period), with n = 95, still has its normal value, but with n = 105 the maximum was reached. From this it can be concluded that the start of variation reduces to n = 100 ± 5; that is, in this case the start of variation can be determined with an accuracy of about 8^h.

The mean value of the atmospheric density was between n = 15 and n = 95 and, in conformity with what was said earlier, was

$$\rho_M = (1.77 \pm 1.62).10^{-14}\ \text{g/cm}^3$$

For the maximum we get (for n = 105) $\rho = (9.13 \pm 3.56)\ 10^{-14}$ g/cm^3. If we wish to estimate the amplitude of the variations in atmospheric density, we must, of course, take into account also errors in the values we have determined. But since we now wish to show only the reality of the short-term variations in atmospheric density, we calculate the minimum amplitude of the density variations by the following formula: /13

$$A_{min} = \frac{(\rho_i \mp \varepsilon_{\rho_i}) - (\rho_M \pm \varepsilon_{\rho_M})}{\rho_M \pm \varepsilon_{\rho_M}},$$

where ρ_i is the running value of the atmospheric density; ρ_M is the mean value; ε_{ρ_i}, ε_{ρ_M} are the mean square errors of the corresponding values of the atmospheric density (the upper signs are used in the case $\rho_i > \rho_M$, the lower signs in the opposite case. It can be assumed that in reality the amplitude of the variations is greater than that calculated.

1960-05-3

Sept. 17-27, 1964

t_0 = Sept. 17, 01^h 49.7225^m

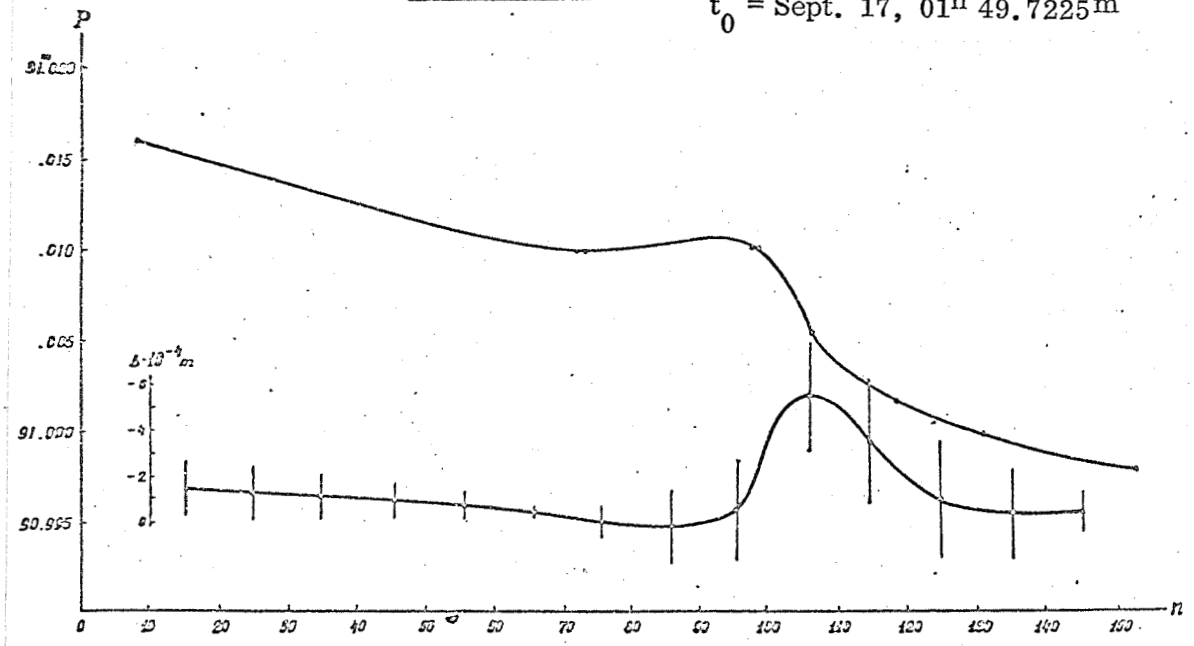


Figure 1.

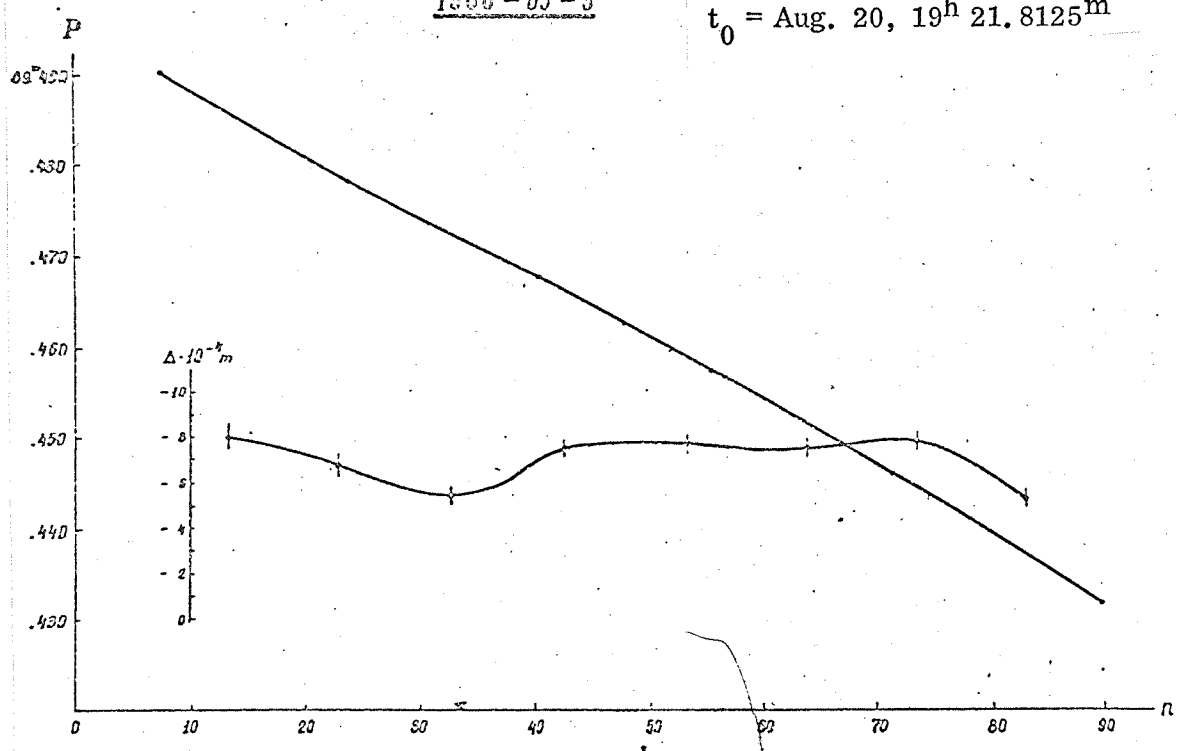

1960 - 05 - 3
Aug. 20-26, 1965
t_0 = Aug. 20, 19h 21.8125m
P
.480
.470
.460
.450
.440
.430
Δ·10⁻⁴m
-10
- 8
- 6
- 4
- 2
0
0
10
20
30
40
50
60
70
80
90
n

Figure 2.

From this formula we find that in the case being examined the amplitude of the variations in atmospheric density A = 64.3%, within a two-day interval.

In Fig. 2. (satellite 1960-05-3, Aug. 20-26, 1965) it is also possible to see the short-term variation in period. The amplitude of the variation is not so great as in the preceding case, but is several times greater than the amplitude of the mean square error. Unfortunately, we do not have the values relating to $n<13$, so that it is not possible to determine uniquely where the start of the variation lies. At any rate, it can be concluded that the minimum lies at n = 33 and that novariations are found from n = 43 to n = 73. Because of the fact that the available observation interval is small (Aug. 20-26), it is impossible to determine whether the value of the density in the interval from n = 43 to n = 73 corresponds to the normal value; in this case we have a short-term decrease in atmospheric density, which has a minimum at n = 33. But it is also possible that the "normal" atmospheric density value is found precisely at n = 30; and in this case the interval between n = 33 and n = 83 must be considered as the place where an increase in atmospheric density occurred (with a very insignificant maximum), lasting about 3.5 days. At any rate, a short-term variation in density is observed here, the start of which (between n = 33 and n = 43) can again be established with an accuracy of $8 \div 10^{h}$. /15

The mean value of the density turns out to be

$$\rho_{M} = (10.34 \pm 0.58).10^{-14} \text{ g/cm}^3$$

and for the minimum (n = 33)

$$\rho = (7.17 \pm 0.58).10^{-14} \text{ g/cm}^3.$$

This corresponds to a minimum amplitude A = 20.6%.

Shown in Figs. 3 and 4 are the variations in period of the satellite 1965-06-1 in August and September 1965. The variations are the same in nature in both intervals, although there are essential differences: 1) in August the distance between the two maxima is D = 30 n, and in September D = 60 n; 2) the amplitude of the variation in September is two times greater than in August. The shape of the curves enables us to assume that we are observing here periodic variations with an attenuating periods. This possibility is probably not excluded, but it is hardly possible to draw definite conclusions from this material, which contains a relatively short time interval. Large variations in amplitude of the density fluctuations apparently indicate that, in all probability, not only variations in atmospheric density govern the variations in satellite orbital period, but also, e.g., variations in the effective area of the cross-section. If, despite this fact, we speak of variations in density, we do so because we have no better explanation at hand.

The mean values of the atmospheric density, as determined from the variations in period, are:

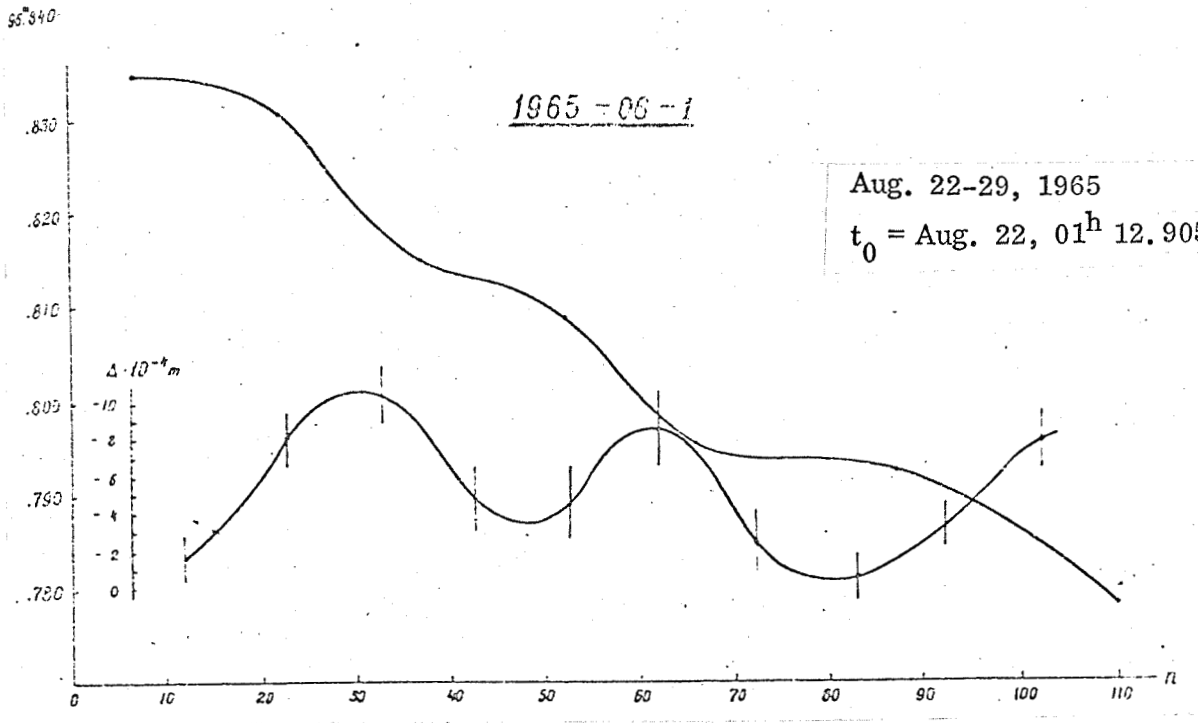
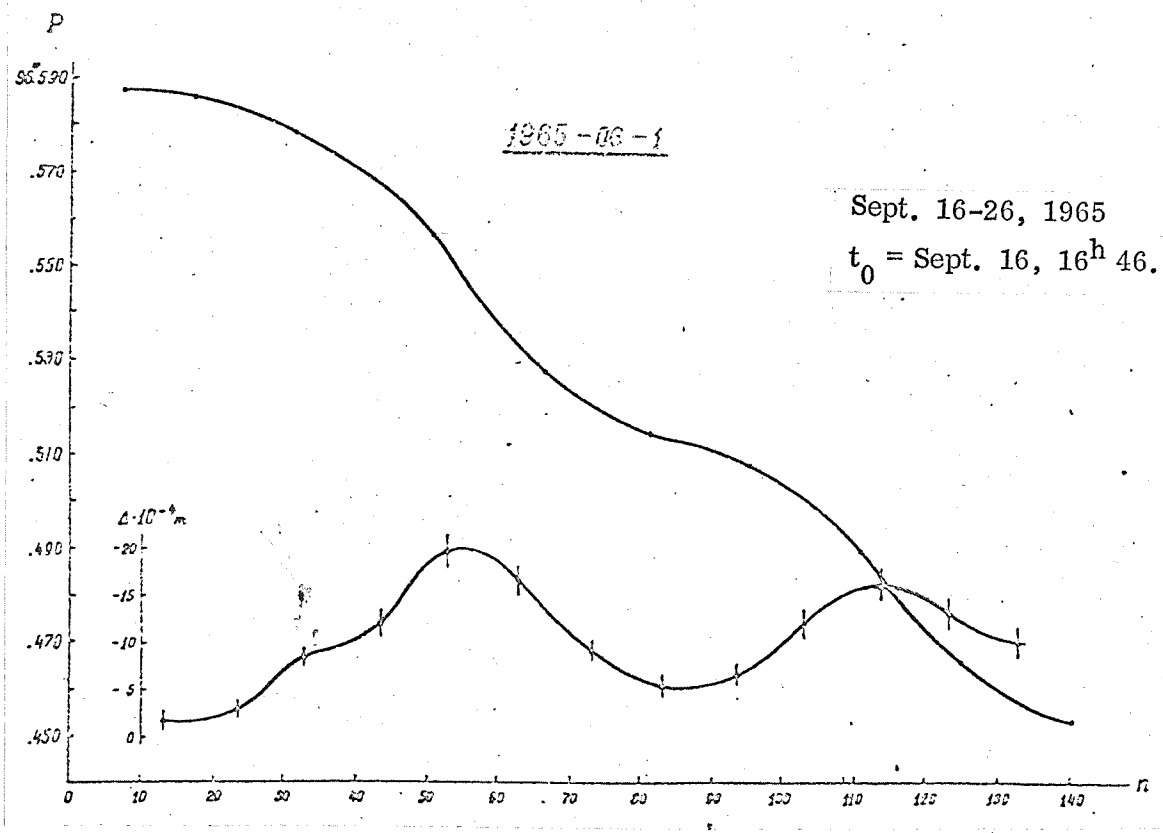

95.840
.830
.820
.810
.800
.790
.780
1965 - 06 - 1
Aug. 22-29, 1965
t_0 = Aug. 22, 01^h 12.9052^m
$\Delta \cdot 10^{-4}m$
-10
-8
-6
-4
-2
0
0
10
20
30
40
50
60
70
80
90
100
110
n

Figure 3.



Sept. 16-26, 1965

t_0 = Sept. 16, 16^h 46.1063^m

Figure 4.

August, 1965 $\rho_M = (26.45 \pm 7.67)\ 10^{-15}$ g/cm^3

September, 1965 $\rho_M = (49.58 \pm 6.50)\ 10^{-15}$ g/cm^3.

If we again calculate the minimum amplitudes, we get the following values for the individual epochs:

August 1965	n = 13	A = - 21.9%
	n = 33	A = + 26.0%
	n = 83	A = - 54.0%
September 1965	n = 13	A = - 68.2%
	n = 53	A = + 59.5%
	n = 113	A = + 25.7%

These data, just as those determined above, create the impression that the variations in atmospheric density have a microstructure, which has not been studied up to the present because of the lack of appropriate methods. In this respect, the observations of the INTEROBS program take on special significance, and in connection with the increase in solar activity will further the study and clarification of the mechanism of the phenomena occurring in the atmosphere.

TABLE 1 /16

Object: 1960-05-03

t_0 = Aug. 19, 1963 19^h 31.6303^m

Epoch n_P	Draconic period P_Ω	Epoch n_Δ	Period variation in one revolution Δ
I5	91^m.9590 ± I5	20	- 0^m.00048 ± 2I
25	9542 ± I5	30	- 35 ± 32
35	9507 ± 28	40	- I5 ± 35
45	9492 ± I8	50	- 05 ± 20
55	9487 ± 09	60	- 05 ± I5
65	9482 ± I2	70	- I0 ± 25
75	9472 ± 22	80	- 2I ± 40
85	945I ± 33	90	- 20 ± 46
95	943I ± 32	I00	- I2 ± 45
I05	9419 ± 3I	II0	- 0I ± 34
II5	94I8 ± I4	I20	- 07 ± I7
I25	94II ± I0	I30	- 20 ± II
I35	9399 ± 05	I40	- 2I ± I0
I45	9370 ± 09	I50	- 08 ± I4
I55	9362 ± II	I60	- 05 ± I4
I65	91^m.9357 ± I3		

TABLE 1 (continued)

Object: 1960-05-03
t_0 = Aug. 7, 1964 00^h 37.0766^m

Epoch n_p	Draconic period P_Ω	Epoch n_Δ	Period variation in one revolution Δ
I5	9I.^{m}I529 ± 0I	20	- 0.^{c}00003 ± 02
25	I520 ± 02	30	- I0 ± 04
35	I5I0 ± 03	40	- 09 ± 06
45	I50I ± 05	50	- I0 ± 07
55	I49I ± 05	60	- 09 ± 07
65	I482 ± 05	70	- I0 ± 06
75	I472 ± 03	80	- 09 ± 05
85	9I.^{m}I463 ± 04		

Object: 1960-05-03 /17
t_0 = Sept. 17, 1964 01^h 49.0028

n_p	P_Ω	n_Δ	Δ
I0	9I.^{m}0I63 ± I0	I5	- 0.^{m}000I4 ± I3
20	0I49 ± 09	25	- I3 ± I2
30	0I36 ± 08	35	- I2 ± I0
40	0I24 ± 06	45	- I0 ± 08
50	0II4 ± 05	55	- 06 ± 06
60	0I03 ± 03	65	- 04 ± 0I
70	0I04 ± 02	75	- 00 ± 07
80	0I04 ± 07	85	- 00 ± I6
90	0I04 ± I4	95	- 06 ± 22
I00	0098 ± I7	I05	- 6I ± 24
II0	0037 ± I7	II5	- 34 ± 26
I20	0003 ± 20	I25	- I0 ± 27
I30	90.^{m}9998 ± I8	I35	- 06 ± 20
I40	9987 ± 09	I45	- 07 ± 09
I50	90.^{m}9980 ± 0I		

TABLE 1 (continued)

Object: 1960-05-03
t_0 = Aug. 20, 1965 19^h 21.8125^m

Epoch n_p	Draconic period P_Ω	Epoch n	Period variation in one revolution Δ
08	$89.^m4907 \pm 06$	I3	$- 0.^m00079 \pm 07$
I8	4828 ± 05	23	- 70 ± 06
28	4758 ± 03	33	- 53 ± 04
38	4705 ± 03	43	- 74 ± 04
48	4631 ± 08	53	- 75 ± 04
58	4556 ± 03	63	- 72 ± 04
68	4484 ± 03	73	- 83 ± 05
78	4401 ± 03	88	- 50 ± 05
88	$89.^m4351 \pm 04$		

Object: 1963-43-01
t_0 = March 11, 1964 02^h 11.5348^m

/18

n_p	P_Ω	n_Δ	Δ
07	$102.^m3841 \pm 18$	I2	- 0. 00048 ± 28
I7	3793 ± 22	22	- 48 ± 33
27	3745 ± 25	32	- 44 ± 34
37	3701 ± 23	42	+ 01 ± 28
47	3702 ± I6	52	+ I5 ± I7
57	3717 ± 07	62	+ I5 ± 08
67	$102.^m3732 \pm 08$		

Object: 1963-43-01
t_0 = April 9, 1964 19^h 29.8451^m

n_p	P_Ω	n_Δ	Δ
07	$102.^m3631 \pm 07$	I2	+ 0. 00007 ± I0
I7	3644 ± 07	22	+ I0 ± 09
27	3654 ± 05	32	+ 06 ± 05
37	3660 ± 02	43	+ 00 ± 03
47	3660 ± 02	52	+ 02 ± 04
57	3662 ± 03	62	+ 04 ± 04
67	3666 ± 03	72	+ 08 ± 04
77	$102.^m3674 \pm 08$		

TABLE 1 (continued)

Object: 1965-06-01
t_0 = Aug. 22, 1965 01^h 12.9052^m

Epoch n_p	Draconic period P_Ω	Epoch n_Δ	Period variation in one revolution Δ
08	$99^m.5198 \pm 10$	13	$+ 0^m.00002 \pm 13$
18	5200 ± 08	23	+ 02 ± 09
28	5202 ± 05	33	+ 05 ± 07
38	5207 ± 05	43	+ 05 ± 07
48	5212 ± 05	53	+ 05 ± 07
58	5217 ± 05	63	+ 03 ± 07
68	5214 ± 05	73	- 04 ± 07
78	5210 ± 05	83	- 01 ± 09
88	5209 ± 08	93	- 08 ± 14
98	$99^m.5201 \pm 11$		

Object: 1965-06-01
t_0 = Aug. 22, 1965 01^h 12.9052^m

/19

n_p	P_Ω	n_Δ	Δ
08	$96^m.8346 \pm 07$	13	$- 0^m.00017 \pm 12$
18	8329 ± 09	23	- 80 ± 14
28	8249 ± 11	33	- 103 ± 16
38	8146 ± 12	43	- 46 ± 17
48	8100 ± 13	53	- 43 ± 19
58	8057 ± 14	63	- 93 ± 20
68	7964 ± 14	73	- 26 ± 18
78	7938 ± 11	83	- 05 ± 13
88	7933 ± 07	93	- 41 ± 12
98	7892 ± 09	103	- 79 ± 16
108	$96^m.7813 \pm 13$		

TABLE 1 (continued)

Object: 1965-06-01
t_0 = Sept. 16, 1965 18^h 46.1063^m

Epoch n_P	Draconic period P_Ω	Epoch n_Δ	Period variations in one revolution Δ
08	$96.^m5883 \pm 08$	I3	$-0.^m000I8 \pm I0$
I8	5885 ± 07	23	− 3I ± 09
28	5884 ± 06	33	− 79 ± I0
38	5755 ± 09	43	− I26 ± I5
48	5692 ± I3	53	− 204 ± I8
58	5425 ± I2	63	− I67 ± I6
68	5258 ± I0	73	− 76 ± I3
78	5I82 ± 08	83	− 53 ± I2
88	5I29 ± 09	93	− 67 ± 93
98	5062 ± 09	I03	− I23 ± I4
I08	4939 ± II	II3	− I62 ± I6
II8	4777 ± II	I23	− I40 ± I6
I28	4637 ± I2	I33	− 93 ± I5
I38	$96.^m4544 \pm I0$		

TABLE 2

/20

Object: 1960-05-03
t_0 = Sept. 17, 1964 01^h 49.0028^m

n	ρ ($I0^{-I4}$ g/cm^3)	Mean value
I5	2.04 ± I.90	
25	I.90 ± I.25	
35	I.77 ± I.47	
45	I.44 ± I.I5	
55	0.95 ± 0.95	
65	0.54 ± 0.05	
95	0.95 ± 3.52	ρ_M = (I.77 ± I.62).$I0^{-I4}$ g/cm^3
I05	9.I2 ± 3.56	
II5	5.03 ± 3.82	
I25	I.49 ± 2.53	
I35	0.95 ± 3.I4	
I45	I.09 ± I.4I	

TABLE 2 (continued)

Object: 1960-05-03
t_0 = Aug. 20, 1965 19^h 21.8125^m

n	ρ (10^{-14} g/cm^3)	Mean value
13	10.70 ± 1.04	
23	9.49 ± 0.77	
33	7.17 ± 0.58	
43	10.09 ± 0.53	
53	10.27 ± 0.57	$\rho_M = (10.34 \pm 0.58).10^{-14}$ g/cm^3
63	9.75 ± 0.58	
73	11.51 ± 0.61	
83	6.81 ± 0.67	

Object: 1965-06-01 /21
t_0 = Aug. 22, 1965 01^h 12.9052^m

n	ρ (10^{-15} g/cm^3)	
13	8.63 ± 6.04	
23	39.82 ± 6.97	
33	50.87 ± 7.88	
43	23.04 ± 8.52	
53	21.12 ± 8.85	$\rho_M = (26.45 \pm 7.67).10^{-15}$ g/cm^3
63	46.09 ± 9.91	
73	12.97 ± 8.94	
83	2.40 ± 6.24	
93	20.17 + 5.85	
103	39.39 ± 7.88	

Object: 1965-06-01
t_0 = Sept. 16, 1965 18^h 46.1063^m

n	ρ (10^{-15} g/cm^3)	
13	8.83 ± 4.86	
23	14.87 ± 4.31	
33	38.12 ± 4.80	
43	60.43 ± 7.19	
53	98.10 ± 8.63	
63	80.45 ± 7.72	$\rho_M = (49.58 \pm 6.50).10^{-15}$ g/cm^3
73	36.74 ± 6.28	
83	25.58 ± 5.78	
93	32.09 ± 5.74	
103	59.08 ± 6.68	
113	78.16 ± 7.66	
123	67.46 ± 7.69	
133	44.66 ± 7.14	

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Station No. 1113
Baja, Hungarian People's Republic.

Received
September 29, 1967

Translated for the National Aeronautics and Space Administration by Scripta Technica, Inc. NASW-2036.